NASA ROBOTICS PROGRAMS: FUTURE DIRECTIONS AND RELEVANCE TO DoD

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Symposium on Unmanned Ground Vehicle Technology
Institute for Defense Analyses
October 24-26,1995

NASA TELEROBOTICS TECHNOLOGY

Program Goals

- Develop and deliver the technologies required to allow a minimum of 50% of all on-orbit and planetary surface operations in the year 2004 to be conducted telerobotically
- Positively impact the growth of the terrestrial robotics industry in the United States
- Foster the science and technology of remote telerobotics leading to increases in operational capability, safety, cost effectiveness, and probability of success of NASA missions.

The program is currently divided into primary application areas which include robotic planetary surface exploration and on-orbit servicing of satellites and platforms. This paper reviews a planned mission set, and the desired capabilities and technology requirements which emerge from the most prominent missions in this set. The paper also provides examples of salient technologies which may have important relevance to future military missions: mobile miniaturized science laboratories for planetary exploration; telepresence and remote control for operation and maintenance of International Space Station Alpha; and use of telerobotics technology developed for space in such terrestrial applications as demining, search and rescue, and harvesting operations.

NASA TELEROBOTICS TECHNOLOGY

Applicable Missions

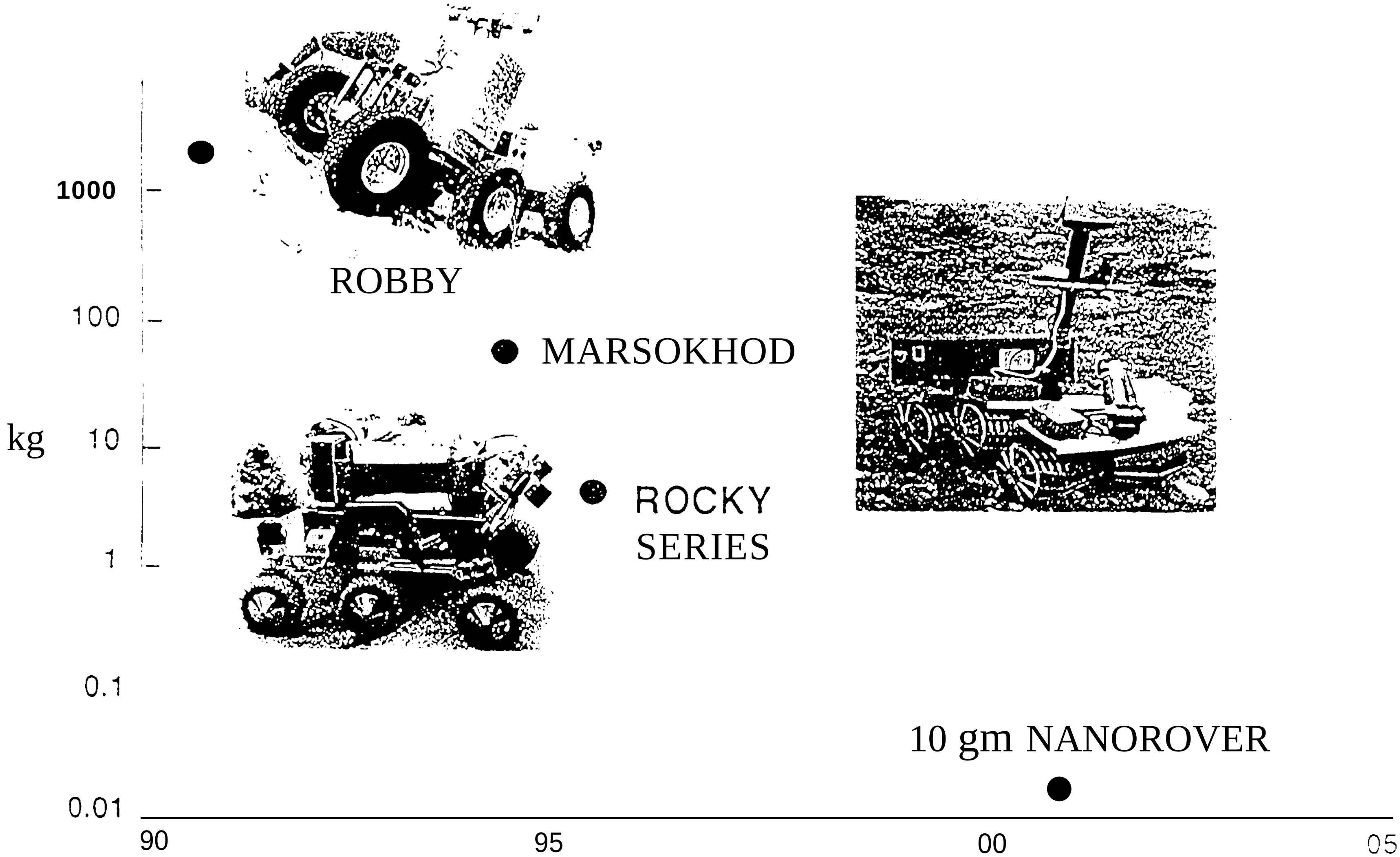
- Space Science -
  - Mars Surface Exploration -
  - Comet and Small Body Exploration -
  - Inner Planets
- ISSA -
  - Assembly
  - Maintenance Operations
- On-Orbit Flight Experiments

NASA TELEROBOTICS TECHNOLOGY

Applicable Missions

- SPACE SCIENCE MISSIONS: Requirements for this program emerge from missions that implement NASA's thrust in Mars exploration. The baseline mission is Mars Pathfinder, to be launched in late '96 with a small rover, named Sojourner, based on technology from this program. This mission is a precursor to the Mars Surveyor Program, with lander missions in '98, 'O 1, '03, and '05. In the more distant horizon, are sample-retum-to-Earth missions in '05 and '07. Comet mission requirements are typified by the European Space Agency (ESA) Rosetta Champolion mission to be launched in '03. The mission will utilize remote sensing and in-situ analyses to characterize the nucleus and coma of a short period comet for approximately one year. NASA will provide at least one surface science package for this ESA mission. Various types of Venus missions provide yet another set of requirements. Launch opportunities exist within the NASA Discovery program as early as '02 for robotic balloon missions, and as early as '04 for lander missions.
- INTERNATIONAL SPACE STATION ALPHA: Applicability of robotics technology to space station requirements for assembly, maintenance and operations is one of the driving goals for this program. Among these three, maintenance appears to be the most important requirement, although the other two are also important. The Extravehicular Work System (EWS) Astronaut Assistant. with projected launch dates of '00 and '02, would assist a nearby astronaut in the conduct of assembly and maintenance operations. The first example of the Astronaut Assistant is the AERCam (Autonomous EVA Camera), a small free-flying robotic platform, that can provide currently unavailable video viewpoints in the vicinity of the Shuttle and its payloads and for the ISSA, and that will increase efficiency and reduce risks of the external operations.
- ON-ORBIT SERVICING FLIGHT EXPERIMENTS: In addition to technology flight experiments driven by ISSA requirements, there are several proposed flight experiments of free-flying servicing robots. The most prominent, and promising, such robot is the Ranger flight experiment, with a planned launch date of '97, will demonstrate system-level capabilities for on-orbit satellite servicing. The first Hubble Telescope servicing mission in '94 demonstrated the challenges in meeting its requirements for on-orbit servicing. The Telerobotics program closely monitor the servicing requirements for Hubble servicing missions, and responds to the opportunities. These flight experiments are an intermediate, and in fact critical, step between the demonstration of robotics technology in terrestrial environments and routine use of this technology in mission operations.

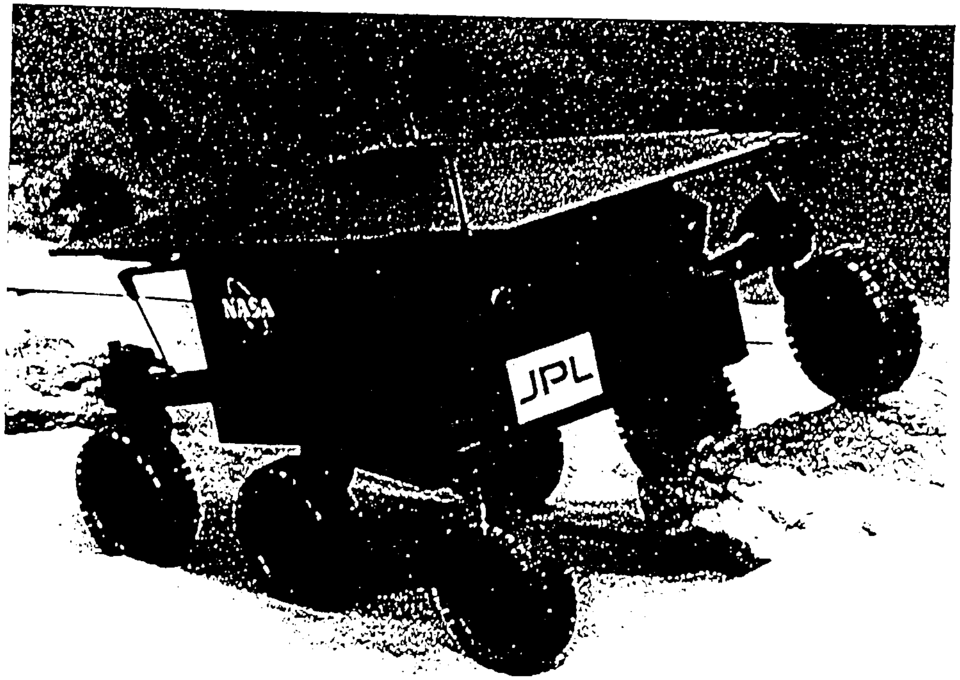
JPL MICROROVER MASS TRENDS



JPL

MARS PATHFINDER ROVER TECHNOLOGY EXPERIMENT

- FIRST ROVER ON MARS
  - **LAUNCH** DEC '96
  - ARRIVE JUL '97
- SMALL, LOW COST, AND FAST DEVELOPMENT (10 Kg, $25M, 3 YEARS)
- MISSION:
  - VISIT GEOLOGICALLY SIGNIFICANT ROCKS IN THE VICINITY OF LANDER
  - TEST ROCKS AND SOIL BY MEANS OF PLACING **AN** ALPHA-PROTON-X-RAY SPECTROMETER
  - IMAGE LANDER
  - **PERFORM TERRAIN** AND MOBILITY EXPERIMENTS



Planetary Surface Exploration Technology Needs

N d and Con a n	**T hno g R qu m n**
A M	g W 0 Ro
S Ro S m	V m
Ex Fr R	Sm End Ef
Emp m	Ro B d M
Subsurface Sampling	Micropenetrators
Survive Many Days	Thermal Regulation
Receive Commands Once/ Day	Rover Autonomy
Cheaper, Better Missions	Tech. & Flight System Correlation

Planetary Surface Exploration Technology Needs

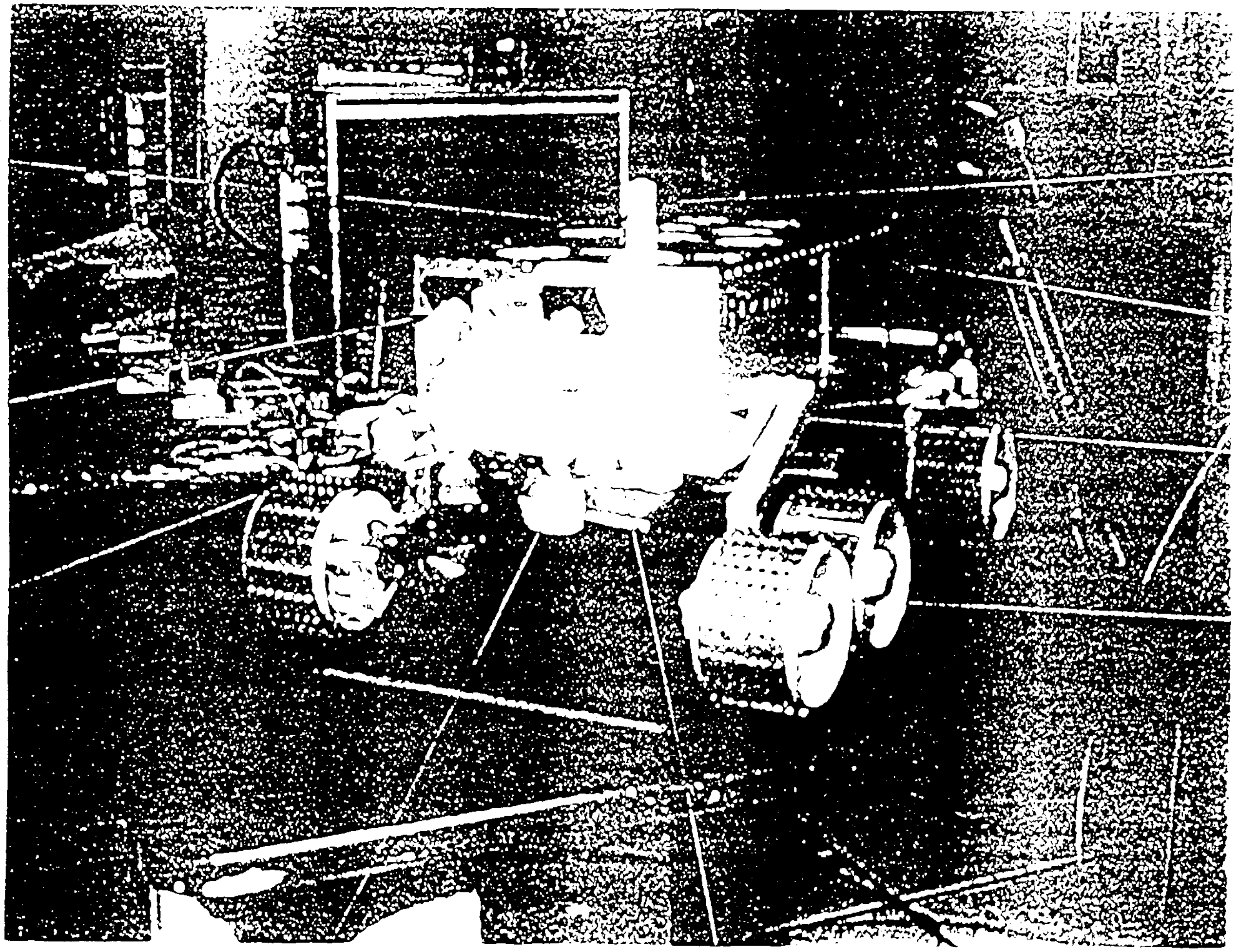
- Reducing cost, while simultaneously enabling new and exciting capabilities in surface expiration, is one of major goals of the next-generation of space science missions. Acquisition of surface science is required for a wide range of missions: to Mars, to small bodies, and to the inner planets. Reduced mass is a critical requirement because it enables smaller, less costly missions, and more of them. This constraint implies that the corresponding robots for these missions must satisfy very stringent mass allocations. The series of missions planned for the late 1990's and beyond by the Mars Surveyor Program provide the opportunity for important new capabilities in miniaturized, survivable surface rovers and sampling systems. The table on the previous page provides a summary of the capability requirements, the constraints under which these requirements must be met, and an indication of the required technologies.
- Affordable surface mobility in the vicinity of a lander is a desired capability because it enables: em placement and deployment of scientific instruments at various locations; soil and rock sampling at multiple sites, as well as the characterization of their material properties; and serendipitous exploration of sites which would otherwise go unexpired. Collecting rock and soil samples, and preparing them for in-situ analyses. are complementary requirement to surface mobility. A typical requirement for sample acquisition is that of acquiring a 10 cu. cm sample, at a subsurface depth of **20** cm depth. This may involve boring a hole 1-2 cm in diameter. The samples must not be heated or vertically mixed in achieving the subsurface sample operations. Small penetrators are emerging technological options to achieve such subsurface sampling. Besides' cost, an additional constraint for Mars exploration is that of vehicle survivability in the harsh surface temperature environment. Because communication of commands from Earth to Mars can only be achieved once a day, it is necessary for the rover to operate by itself for an entire day at least, and conduct multiple science acquisition operations with a single command uplink.

Miniature Planetary Rovers for Mars Pathfinder and Beyond

- The Sojourner microrover is a key technological experiment in the 1996 Pathfinder mission to Mars. The microrover has a mass of about 13 kg, including the lander mass required to support the microrover system. Sojourner will demonstrate technologies in autonomous deployment, hazard-avoidance and navigation, and scientific instrument emplacement. It will also provide experimental data about the mechanical properties of the Martial soil.
- In parallel with the development of the Sojourner microrover flight system, the NASA Telerobotics Program, within the NASA Office of Space Access and Technology, supports an aggressive technology development program in rover technology aimed at enabling important new capabilities in autonomous navigation, miniaturization, survivability, sampling, and on-board science goal identification.
- The Rocky 7 vehicle shown in the next page is a miniaturized rover designed and built in 1995 for terrestrial experimentation and demonstration. With a mass of about 15kg, it has significantly improved capabilities beyond the Sojourner flight system: a low-mass manipulator for sample acquisition and handling; a low-cost vision system for stereo image acquisition and processing; improved capabilities in hazard detection and avoidance made possible by on-board vision system; increase vehicle autonomy that manifests itself by the ability to execute multiple consecutive tasks with one single command cycle; and autonomous goal identification software that allows the microrover to recognize autonomously when a desired scientific goal has been achieved.

Rocky 7

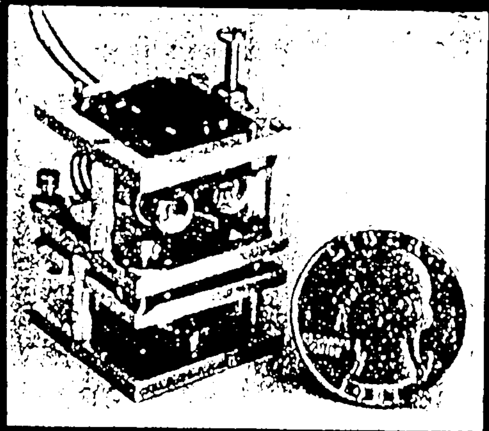
Next Generation Research Microrover



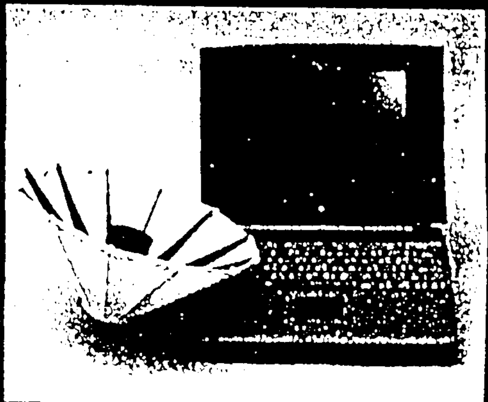
Subsurface Sampling System

- The gathering of surface and subsurface samples for scientific exploration is an important part of such missions. Low mass/power mechanisms for sample acquisition are explored as well as concurrent development of sensors and control methods enabling autonomous operation in materials of unknown composition
- The previous page shows a subsurface sampling system being developed to meet technology needs in cometary sampling, as typified by the JPL/CNES Champollion comet lander (ESA Rosetta mission). The comet sampling system is required to gather several cm3 of material from up to a meter beneath a comet's surface and deliver that sample to multiple on-board instruments within an extremely challenging mass/power budget. A prototype system incorporates multiple sensors not only allowing autonomous operation but also gathering data on material properties as sampling is done. A cryogenic test chamber enables testing of a prototype sampling system in cryogenic comet facsimile materials of various densities.

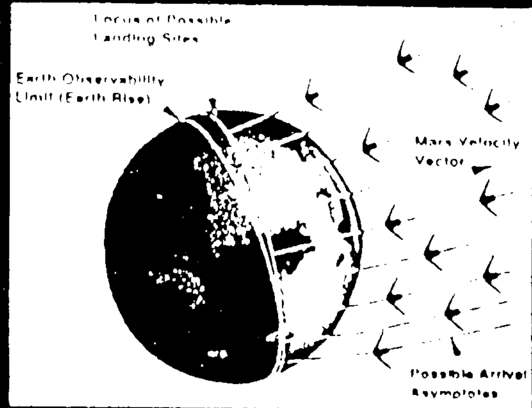
POWERFUL M CRO NSTRUMENTS



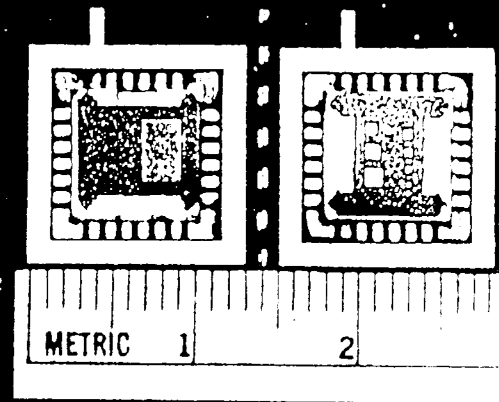
MICROSEISMOMETER



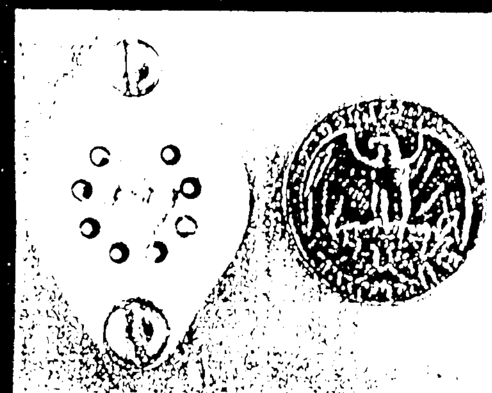
MICRO LANDER



MICROLANDERS ON MARS



MICROMACHINED
PRESSURE SENSOR



MICROMACHINED
DEWPOINT HYGROMETER

EMERGING MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) ENABLE:

- INTEGRATED MICROSENSOR PACKAGES FOR LOW MASS LANDERS AND ORBITERS
- A RANGE OF IN SITU ANALYTIC MEASUREMENTS WITHOUT COSTLY SAMPLE RETURN
- NETWORKS OF MICROLANDER PACKAGES FOR GLOBAL PLANETARY INFORMATION

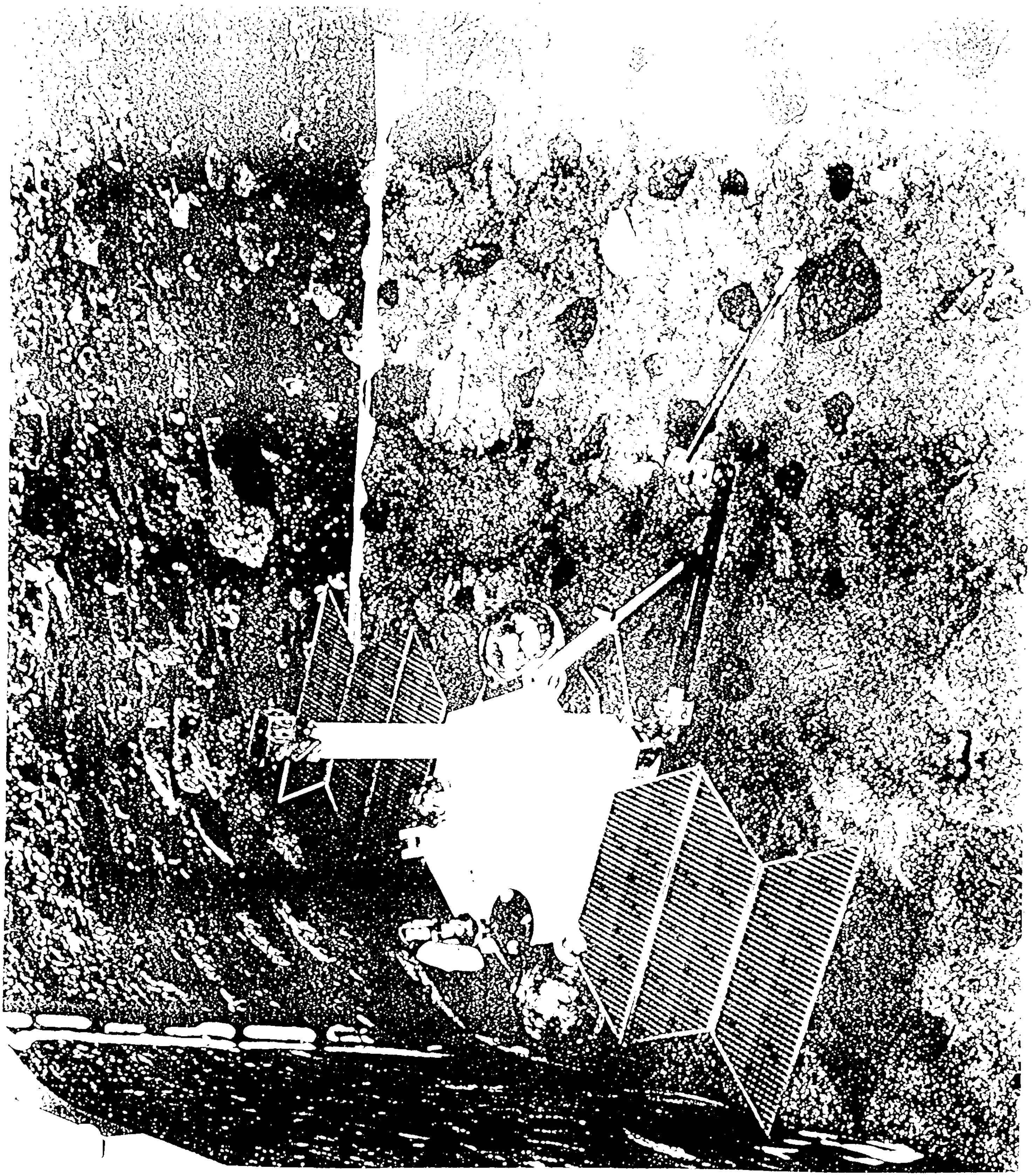
JPL Center for Space Microelectronics Technology

Powerful Microinstruments

- Important technology for Mars and other planetary surface exploration is emerging from the JPL Center for Space Microelectronics Techology (CSMT), under the direction of Dr. C. A. Kukkonen of JPL. This Center is supported by a wide spectrum of government and industrial sponsors. One of the major thrusts in the center is the development of miniaturized sensor technologies. The previous chart illustrates a relatively small sample of such sensor technologies. CSMT is supported by a variety of technology development programs, separate from the NASA Telerobotics Program which is the central topic of this paper. However, there are major activities at this Center, microinstrument development for example, that have concurrent interest to the NASA Telerobotics Program.

Where is the Excitement?

- **Machines with Increasing Intelligence**
  - autonomously identify target goals, confirm task success, and execute concatenated task sequences
- **Machines with Increasing Capability**
  - non-line of sight navigation, sampling of various types (core, chip, etc.), mobile science laboratories
- **New Concepts: distributed, highly robust, localized search**
  - 10-100 gm nanorovers for localized search, combined with lander/rover concepts
  - integrate image sensing with computer processing on a single, low-power VLSI chip



NASA TELEROBOTICS TECHNOLOGY

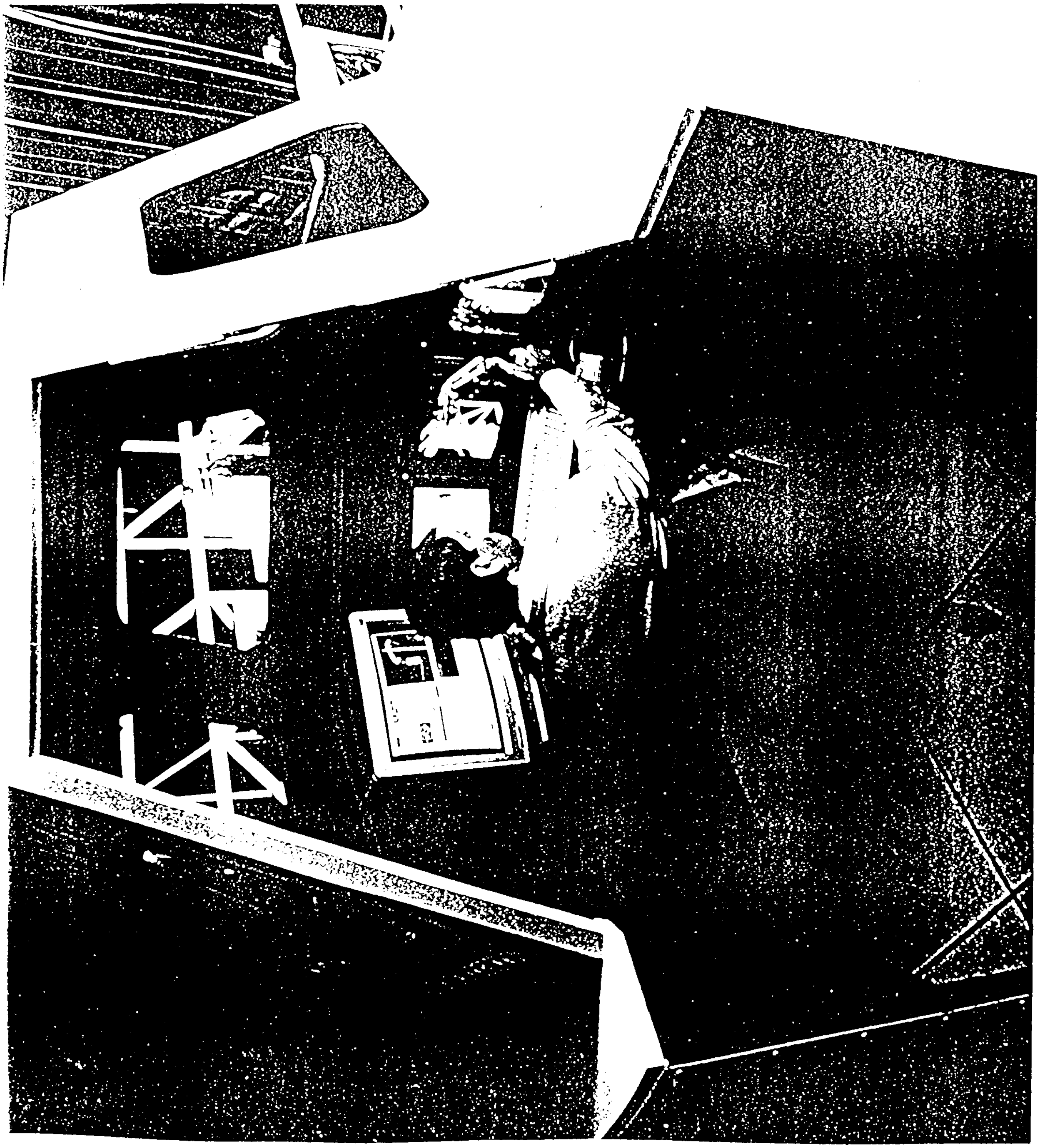
Micro-Lander Dexterous Manipulator

- Acquisition of science in the vicinity of a lander or rover is an important NASA goal in planetary surface exploration. The previous chart shows a terrestrial laboratory prototype of a manipulator that would go to Mars in a mission planned for 1998. The laboratory was set up to develop and demonstrate in a relevant science operations concept a new 3 degree-of-freedom breadboard robotic arm based on a rigid, lightweigh graphite-epoxy telescoping structure. Relative to the Viking era technology, the new arm affords a five-fold reduction in mass and volume, with far greater manipulative dexterity and stowage efficiency.
- Based on the principles of design and electro-mechanical architecture demonstrated in the above laboratory prototype, a UCLA-led Mars Surveyor '98 science team was able to propose a novel lander-based robotic operations concept for surface geology, mineralogy and climatology --with potential to significantly advance our knowledge of that planet relative to use of deck-mounted instrumentation only.

Space Station Robotics

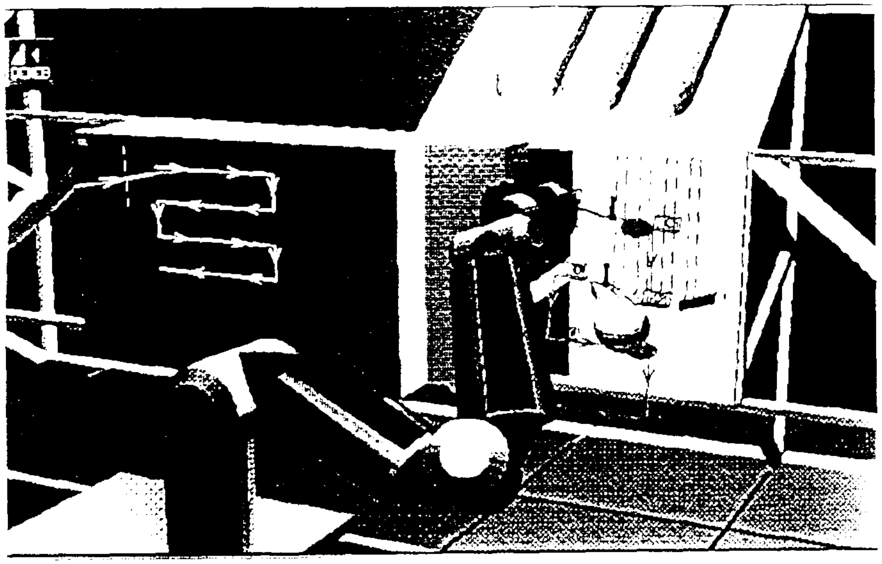
Capability & Technology Requirements

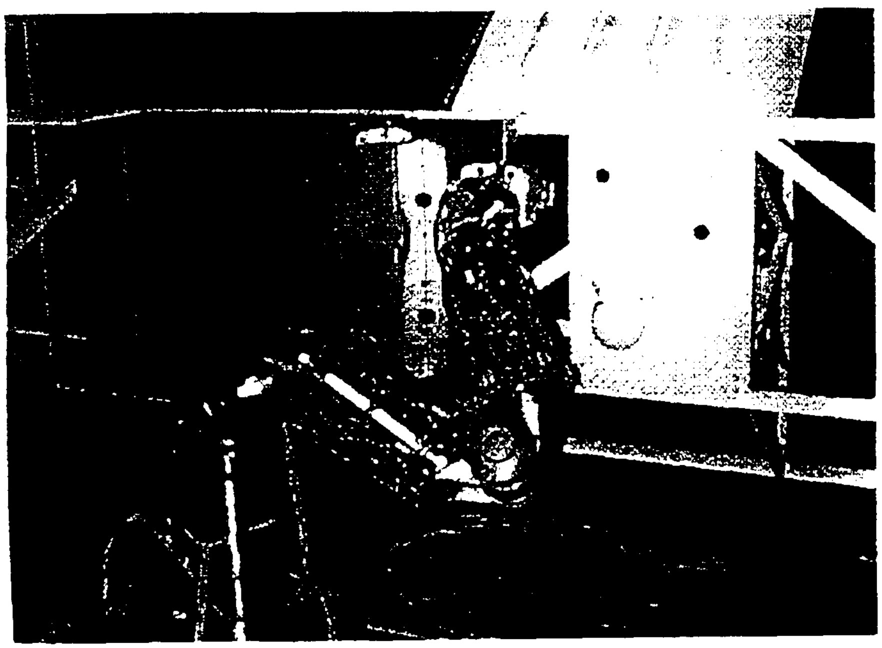
Desired Capability	**Technology Required**
Better Fine Alignment & Mating	Precision Robots & Alignment Systems
Reduced Maintenance Backlog	Faster Robots & Streamlined Sequences
Improved Inspection Procedures	Automated Visual Inspection Robots
Operational Flexibility	Collision Avoidance Systems
More Efficient Robot Task Timelines	More Robot Autonomy
60% More Maintenance Items	Robotic Tooling
Human-Machine Coordinated Ops	Ground Control
Better Robustness & Fault Tolerance	Fault Tolerant Robot Architectures
On-Orbit Robot Task Verification	Verification & Simulation Testbeds



JPL

REMOTE **SURFACE INSPECTION**





ACCOMPLISHMENTS

- Demonstrated **that ground controlled telerobotic inspection of Space Station is feasible**
- **Developed automated visual inspection based upon image differencing**
- **Developed inspection capabilities for detection of gas leaks. temperature changes. and small cracks using additional sensors**
- **Developed motion guides and sensor based collision detection and avoidance technology to enable robot operations in constrained areas** such **as Space Station truss**
- **Transferred new technology to industry: Robotics Research Corp.. RedZone Robotics Inc.**
- **Demonstrated remote telerobotics operations via robotics operations from JSC to JPL**

Space Station Technology

Remote Surface Inspection System

- The previous page shows an illustrative system. typical of the technologies being developed in response to International Space Station Alpha (ISSA) capability desires. This system is intended to assist ground controllers and crew members in conducting anticipated inspection operations.
- Complex space missions require routine and unscheduled inspection for safe operation. A research and development program is being conducted to develop supervised inspection techniques for tedious tasks as an aid to the operator. The telerobotic system. would perform inspection relative to a given reference (e. g., the status of the facility at the time of the last inspection) and alert the operator to potential anomalies for verification and action. One example might be for the inspection of truss struts for micrometeoroid damage and visible cracks on thermal radiator surfaces. Simulation of realistic dynamic lighting conditions is included. In addition, configuration control of manipulators with redundant degrees of freedom pioneered by JPL has been implemented to assure dexterous manipulation near complete structures.
- The baseline inspection task is to teleoperate a robotic arm which carries a pair of "mini-wrist cameras. The operator uses a pair of 3-DOF joysticks and can control the lighting to better *view* the scene. Additional cameras with pan/tilt zoom/focus control are controlled by the operator to observe the arm’s motion and to inspect objects which are far away from the arms. A local-remote architecture is employed so that space and time distances can be effectively treated. Multi-sensor based inspection of gas leak. temperature, and damage is conducted. Subsequently. inspection tasks requiring contact such as Eddy current based crack detection is performed.

REMOTE SURFACE INSPECTION

AUTOMATED FLAW DETECTION

OBJECTIVE: Detection of flaws for simple but time consuming inspections tasks

GENERAL APPROACH: Detection of changes between "before" and "after" images of a scene

TECHNICAL ISSUES:

- Earth orbit ambient light variations for "before" and "after" images

- Misregistration between the "before" and "after" images due to camera positioning repeatability which causes large differences in high contrast regions

TECHNICAL APPROACH:

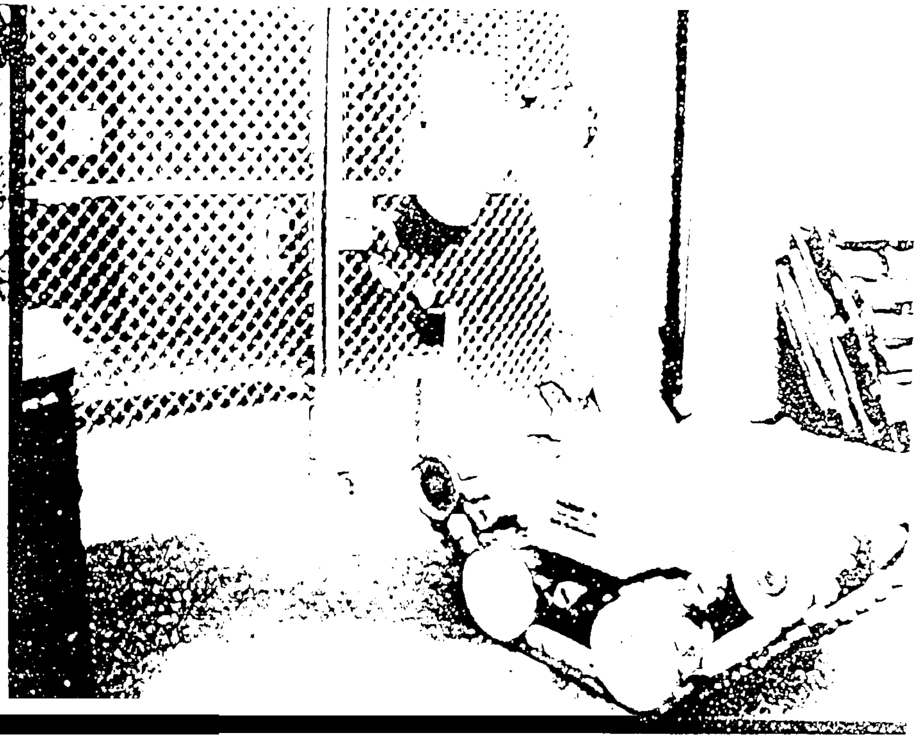
- Subtract image of ambient lit surface from one lit by contro ed lights and improve the results by averaging over many images

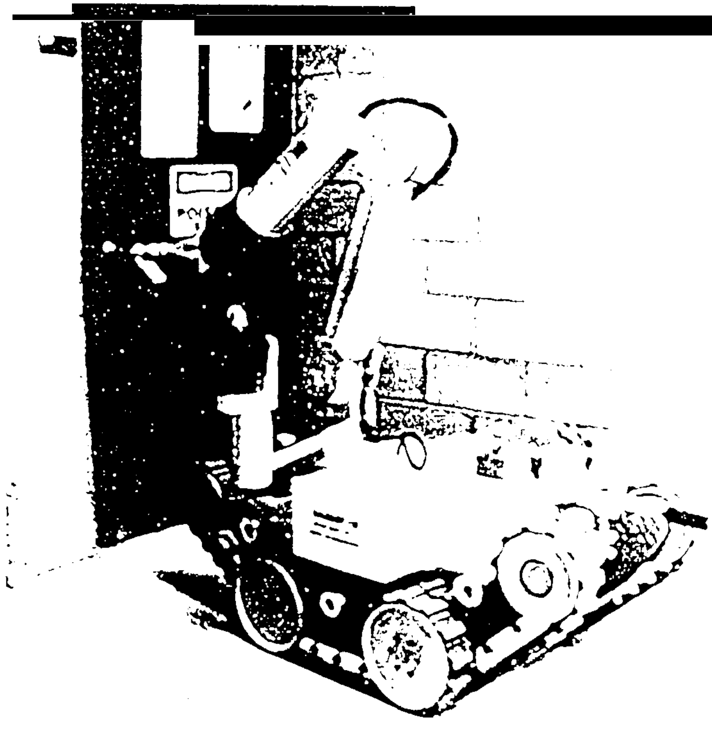
  Develop estimation approach to correct for camera repositioning error

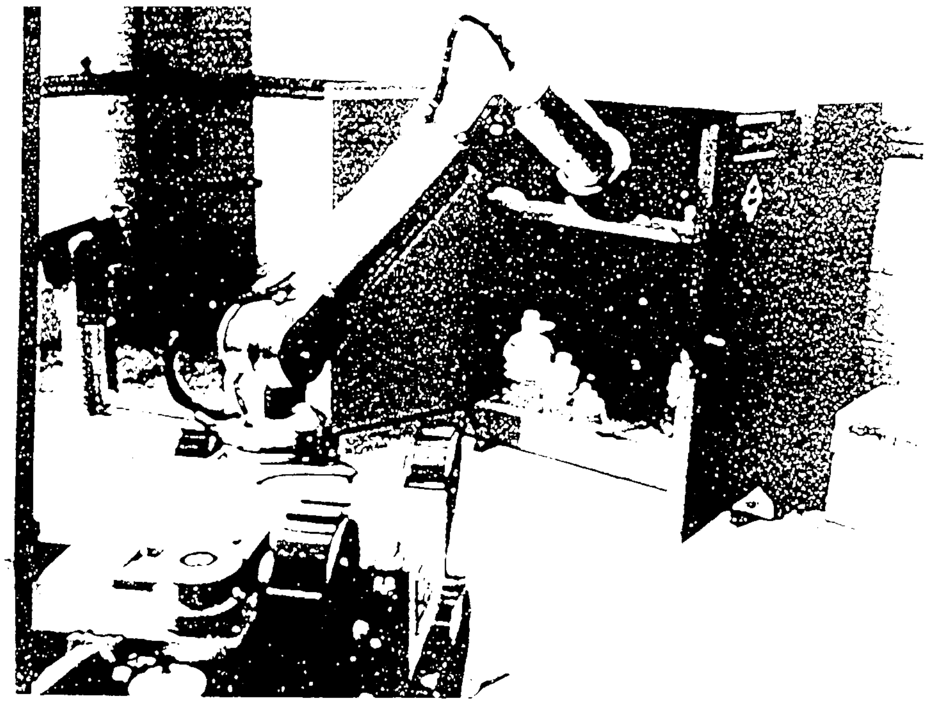
REMOTE SURFACE INSPECTION

- Simulated Solar Lighting
- Continuous Motion Estimation
- Flaw Detection to 3-5 mm
- Automatic Cataloging of Flaws in Data Base
- Benchmarking Detection Capability
- Dexterous 7-DOF Manipulator Motion
- Stereo Viewing and Flyover
- Multi-Sensors: Visual, Pyrometer, Gas, Proximity, Force, Eddy Current
- Snake-Like End-Effecter


JPL FIRE DEPARTMENT
HAZ MAT 1



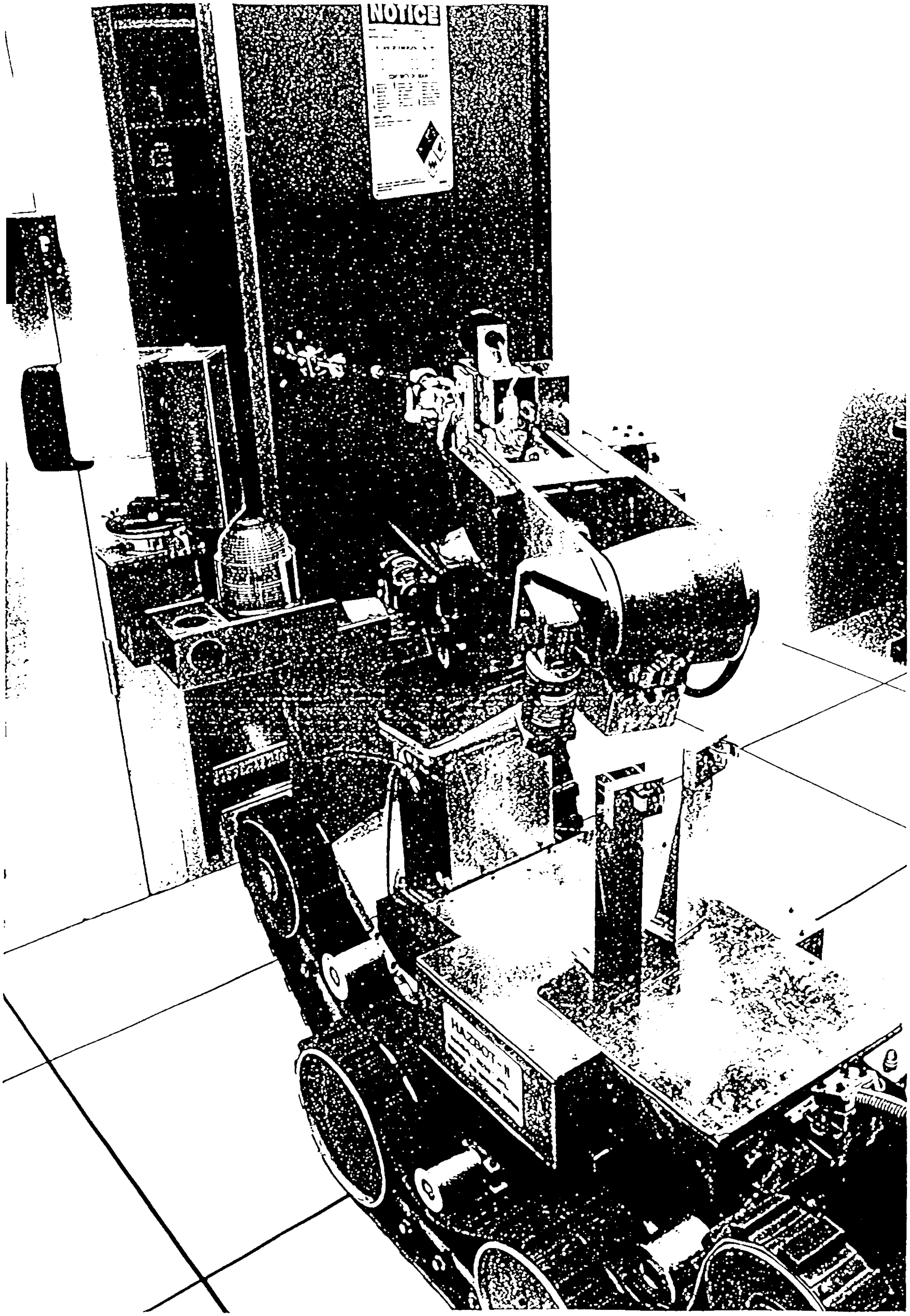




HAZARDOUS OPERATIONS ROBOT

HAZBOT

- A goal of NASA is to develop and demonstrate technology for terrestrial applications with important relevance to space. A teleoperated mobile robot called HAZBOT enables emergency response to remotely explore sites where hazardous materials have accidentally spilled or released, rather than risk the safety of entry team personnel. The primary mission of HAZBOT is first entry and reconnaissance of an incident site-the most dangerous part of a response since the type of materials involved and the magnitude of the spill may not be fully known. During such missions, the robot must first gain entry into the incident site. an effort which may involve climing stairs. unlocking and opening doors. and maneuvering in tight spaces.
- Once the spill is located. an on-board chemical gas sensor is used for material identification. The robot can also aid in remediation or containment of the incident by, for instance. closing a leaking valve, deploying absorbent material, or placing a broken container in secondary containment.
- HAZBOT has been designed to enclose all electrical components and provide internal pressurization, enabling operation in atmospheres that contain combustible vapors. Other system features include a track drive base with front and rear articulating sections for obstacle/stair climbing. a six-degrees-of-freedom manipulator. custom tools for unlocking and opening doors. and 2 color CCD cameras.


NOTICE
HAZBOT - II

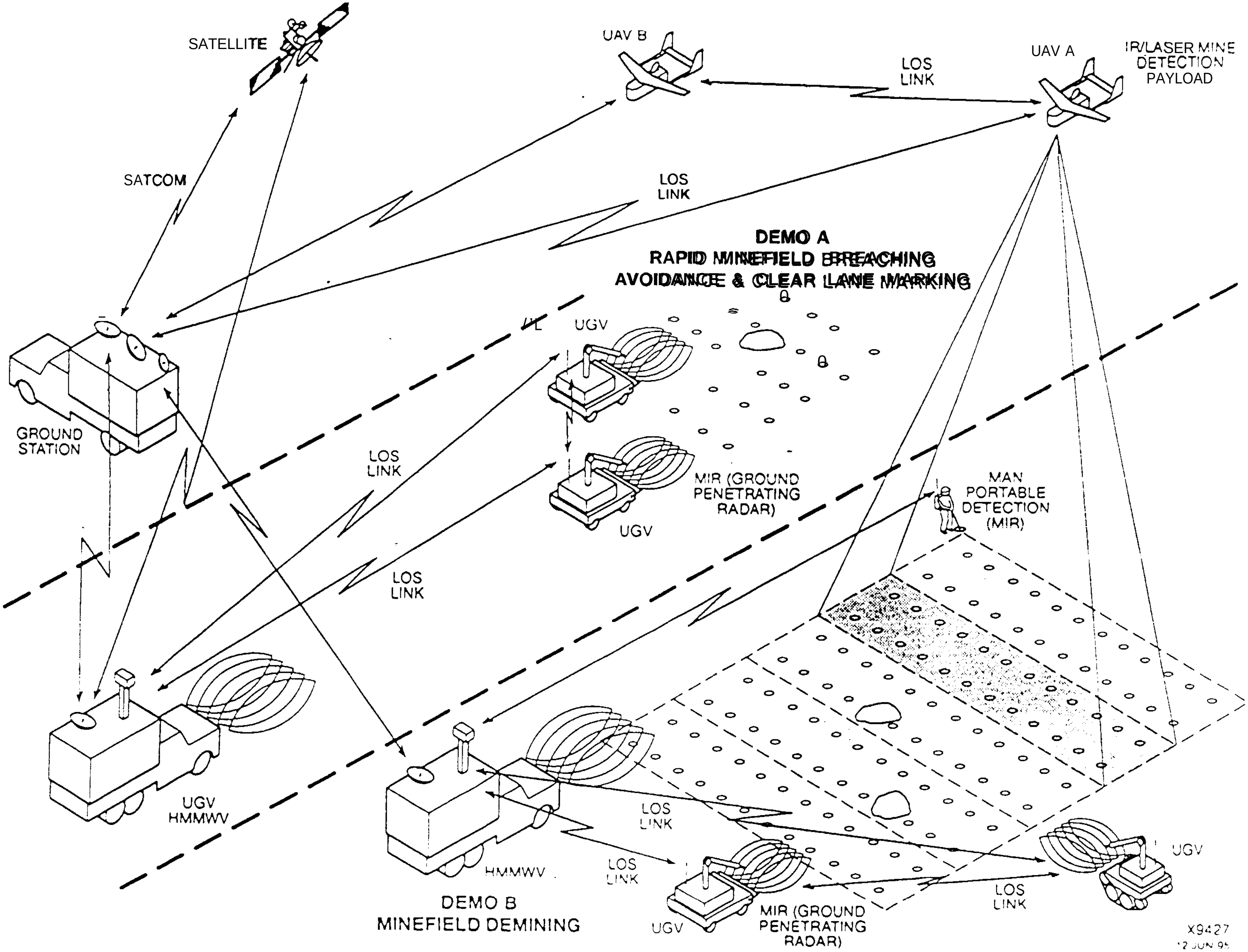
Applicability of NASA Robotics Technology to DoD Missions

- Countering systems
- Defining of anti-tank ordnance
- Reconnaissance - UGV is a “stealth” scout
- Telemedicine - soldier in battlefield
  -
  -
  -
- Surface & subsurface operations
- Convoy loading
- Urban rescue

Robotic Mine Detection/Countermeasures System Concept

- The next page illustrates conceptually a robotic mine detection and countermeasures system. One of the central technologies in such a system is a remotely operated driverless (i. e., unmanned) ground vehicle (UGV) . The concept is based on a hierarchy consisting of different types including various types of airborne systems and UGV'S. The primary mission objective of such a system would be to detect surface and subsurface mines that may be deployed over large surface areas, and to conduct mine deactivation procedures while ensuring outmost safety to operations personnel. The system involves a number of HMMWV vehicles, with each HMMWV supporting a number of smaller autonomous vehicles. In addition to being able to move over a mine field, each miniature UGV system carries deployable ground-penetrating radar sensors capable of mine detection. The sensors are mounted on an articulated robotic platform for sensor deployment and pointing. Sensing and manipulation capabilities are also provided for supportingdemining operations.
- There are many important technological challenges in such a system: 1) Coordination of multiple autonomous mobile vehicles from a more central autonomous system, the HMMWV shown in the figure, that is itself aIso mobile; 2) autonomous detection of mines from a mobile platform by detecting patterns in sensor data; 3) safe digging and mine handling operations; 4) mine hazard avoidance based on sensor data; 5) remote inspection of multiple surface sites, in-situ interpretation of sensor data, and autonomous recognition of location of individual mines and of multiple mine patterns. These technological challenges closely parallel those associated with the previously described NASA technologies in scientific data acquisition from miniaturized rover systems.

Robotic Mine Detection/Countermeasures System Concept



Need for Robotic Mine Countermeasures

- 84-110 million active mines in various countries world wide
- Current manual clearance resulted in neutralization of **85000** mines in 1994
- 2-5 million mines laid every year
- 900 types of mines have been manufactured
- Ratio of clearance to deployment is 1/34
- U. N. demining costs were $70/100K mines
- Total cost for clearance estimated at $33 billion

Mine Detection Sensor Technologies

- **Airborne standoff minefield detection**
  - multispectral airborne sensor suites
    - IR scanner/IR laser reflectometry and polarimetry
    - Passive IR
- **Ground close-proximity detection sensors**
  - multispectral sensors, IR, ground penetrating radar, metal detection
  - IR cameras detect minimal ground and temperature variations due to mines
  - MMW radar can be adapted to detect heterogeneities in the dielectric properties of the ground
  - Magnetic sensors and pulse indication radars can search for anomalous signatures

Correlation of NASA and DoD Mobile Vehicle Missions

UGV Mission	NASA Robotics Vehicle Mission	Common NASA & DoD Technology
Miniature Reconnaisance	Planetary Surface Reconnaisance	Miniature, autonomous vehicles
Countermining	Sensor deployment, surface & subsurface sampling	Powerful microinstruments, robotic mechanisms
Target Detection	Autonomous science target recognition	On-board sensing, processing, perception
Convoy Loading & Resupply	Instrument & rock transport; multivehicle operations	Material transport and handling; vehicle coordination
Convoy Point Leader	Autonomous hazard detection & avoidance	Sensors, on-board intelligent systems

Conflation of NASA and DoD Mobile Vehicle Technologies

Technological Area	**NASA Planetary Rovers**	**DoD Unmanned Ground Vehicles**
Vehicle Size	**15** kg	15kg - 100kg ??
Vehicle Task	Deploy sensors, pick up rocks, soil & subsurface sampling	Deploy sensors, detect subsurface mines
Control Architectures	Hierarchical - orbiter, lander, rover, manipulator, etc.	Hierarchical - UAV, HMMWV UGV, mechanisms, etc.
Navigation	Lander line-of-sight & over the horizon	HMMWV line of sight & over-the-horizon
On-Board Intelligence	Autonomous science object recognition	Autonomous mine detection

Concluding Remarks

- There are many similarities, as well as differences, between NASA telerobotics technologies currently under development by the Telerobotics Program, and the corresponding technologies required for DoD unmanned ground vehicle systems.
- SIMILARITIES: The table in the previous chart shows salient similarities in the areas of vehicle size. control architectures, navigation, and on-board intelligence.
- DIFFERENCES: There are also differences including: the mobile vehicle is physically closer in demining operations than in planetary surface robotics; the mass and volume requirements may not be as severe for robotic ground vehicles; repairing or replacing a vehicle may be possible in ground operations. whereas this is impossible to do in any given planetary mission; issues of time-delay in command transmission and data return between the control site and the remote vehicle may be more pronounced in planetary surface missions.
- There are many opportunities for possible collaboration:
  - joint development of component technologies (e.g. machine perception systems)
  - joint testing of mobile vehicles
  - development of standardized vehicle benchmark and evaluation methodologies
  - systematic testing and evaluation of prototypical end-to-end systems
- **For More Information:**
  - NASA Robotics Program: D. Lavery
    - http://ranier.oact. hq.nasa.gov/telerobotics_page/telerobotics.html
  - JPL Rover and Telerobotics Program: C. R. Weisbin
    - http://1 37.79. 197/trprogram.html
    - Rover and Telerobotics Program Brochure
  - Mars Exploration Technology Program: JPL Internal Document D- 12701

Acknowledgments

The summary of research described in this paper was authored at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors sincerely appreciate and greatly value the collaboration and scientific excellence of all of the members of the Telerobotic Intercenter Working Group (TRIWG) whose efforts are herein described.